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14. ABSTRACT We are studying basic topics of image science related to a new class of speckle-based laser-ranging radars (LADAR) as well as related basic studies of novel integrated imaging and computing systems. Four major research projects are (1) study of speckle patterns including metrology for small pixels on photodetector arrays. (2) Theory and experiments for space and wavelength dependence of speckle from a thick diffuser. (3) study of coded aperture systems. (4) Concepts for imaging through a turbid and turbulent medium. During the final report period, the novel					
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## Report Title

### Final Progress Report: Speckle Research for 3D Imaging LADAR

#### ABSTRACT

We are studying basic topics of image science related to a new class of speckle-based laser-ranging radars (LADAR) as well as related basic studies of novel integrated imaging and computing systems. Four major research projects are (1) study of speckle patterns including metrology for small pixels on photodetector arrays. (2) Theory and experiments for space and wavelength dependence of speckle from a thick diffuser. (3) study of coded aperture systems. (4) Concepts for imaging through a turbid and turbulent medium. During the final report period, the novel phase coded aperture system has been successfully reduced to practice and important technology transfer by OSA talks, presentations by W Chi at two Universities and OSA as well as patent application have been completed. In preparation is a paper describing a liquid crystal phase screen. For speckle study, we completed the reduction to practice of a new space invariant 4F optical system for our ongoing study of propagation in a thick diffuser or a turbid medium. Also, in preparation is a theoretical analysis together with experiments to verify our theoretical prediction for wavelength decorrelation through a series of opal milk glass diffusers. These studies are fundamental achievements related to our future research for imaging through fog or particulates.

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#### List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

##### (a) Papers published in peer-reviewed journals (N/A for none)

Nicholas George, Kedar Khare and Wanli Chi, "Infrared holography using a microbolometer array," Appl. Opt. 47, A7-A12 (2008).

Kaiqin Chu, Nicholas George, and Wanli Chi, "Extended depth of field through unbalanced optical path difference," Appl. Opt. 47, 6895-6903 (2008).

Kaiqin Chu, Nicholas George, and Wanli Chi, "Incoherently combining logarithmic aspheric lenses for extended depth of field," Appl. Opt. 48, 5371-5379 (2009).

Wanli Chi and Nicholas George, "Phase-coded aperture for optical imaging," Optics Commun. 282, 2110-2117 (2009).

Nien-An Chang and Nicholas George, "Speckle in the 4F optical system," Appl. Opt. A13 (2008).

Xi Chen and Nicholas George, Resolution analysis of a gradient-index rod and a gradient index lens array, Appl. Optics 47, 6190 (2008).

Xi Chen, Nicholas George, Gennadiy Agranov, Changmeng Liu and Bob Gravelle, Sensor modulation transfer function measurement using band-limited laser speckle, Optics Express 16, 20047 (2008).

Kedar Khare, Complex representation for 2D signals, Appl Optics 47, E8 (2008).

**Number of Papers published in peer-reviewed journals:** 8.00

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##### (b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

1. Kaiqin Chu, Nicholas George and Wanli Chi, INcoherently combining logarithmic aspheric lens for extended depth of field,; OSA annual meeting, San Joase CA (2009).

2. Kaiqin Chu, Nicholas George and Wanli Chi, "Extending the depth of field through unbalanced OPD, OSA annual meeting, Rochester NY (2008)

3. Nicholas George and Wanli Chi, Emerging integrated computational imaging systems, OSA annual meeting, (Invited Talk) San Jose CA 2009

4. Wanli Chi and Nicholas George, Integrated coded aperture imaging in optical region, OSA annual meeting, Rochester NY 2008.

**Number of Papers published in non peer-reviewed journals:** 4.00

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##### (c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Wanli Chi and Nicholas George, "Correlation optical image system using phase coded aperture," US Patent (filed 2010).

Patents Awarded

1. Nicholas George and Wanli Chi, "Imaging using a multifocal aspheric lens to obtain extended depth of field," US patent 6,927,922 (2005).
2. Nicholas George and Wanli Chi, "Extended depth of field using a multi-focal length lens with a controlled range of spherical aberration and a centrally obscured aperture," US Patent 7,336,430 (2008).
3. Nicholas George and Wanli Chi, "Apparatus and method for extended depth of field imaging," US Patent 7,511,895 (2009).
4. Nicholas George and Wanli Chi, "Imaging using a multifocal aspheric lens to obtain extended depth of field," US Patent 7,554,750 (2009).
5. Nicholas George and Wanli Chi, "Apparatus and method for extended depth of field imaging," US Patent 7,593,161 (2009).

Awards

Graduate Students

NAME	PERCENT SUPPORTED
Paul Zavaterro (Fellowship)	0.00
Nien-An Chang	1.00
Kaiqin Chu	1.00
Joel Bentley	0.40
FTE Equivalent:	2.40
Total Number:	4

Names of Post Doctorates

NAME	PERCENT SUPPORTED
Dr Nien-an Chang (part-time -- Xerox )	0.00
FTE Equivalent:	0.00
Total Number:	1

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### **Names of Faculty Supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Wanli Chi	1.00	No
<b>FTE Equivalent:</b>	<b>1.00</b>	
<b>Total Number:</b>	<b>1</b>	

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### **Names of Under Graduate students supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

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### **Student Metrics**

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 0.00

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### **Names of Personnel receiving masters degrees**

<u>NAME</u>
<b>Total Number:</b>

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### **Names of personnel receiving PhDs**

<u>NAME</u>
<b>Total Number:</b>

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### **Names of other research staff**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

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### **Sub Contractors (DD882)**

## Inventions (DD882)

### 5 Apparatus and method for extended depth of field imaging

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) Y

Foreign Countries of application (5g-2):

5a: Wanli Chi

5f-1a: University of Rochester

5f-c: 275 Hutchison Rd

Rochester NY 14627

5a: Nicholas George

5f-1a: University of Rochester

5f-c: 275 Hutchison Rd

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5f-1a: University of Rochester

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Rochester NY 14627

5a: Wanli Chi

5f-1a: University of Rochester

5f-c: 275 Hutchison Rd

Rochester NY 14627

### 5 Correlation optical image system using phase coded aperture

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) Y

Foreign Countries of application (5g-2):

5a: Nicholas George

5f-1a: University of Rochester

5f-c: 275 Hutchison Rd

Rochester NY 14627

5a: Wanli Chi

5f-1a:

5f-c:

**5 Extended depth of field using a multi-focal length lens with a controlled range of spherical aberration and a centrally obscured aperture**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) Y

Foreign Countries of application (5g-2):

5a: Nicholas George

5f-1a:

5f-c:

5a: Wanli Chi

5f-1a:

5f-c:

**5 Imaging using a multifocal aspheric lens to obtain extended depth of field**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) Y

Foreign Countries of application (5g-2):

5a: Wanli Chi

5f-1a:

5f-c:

5a: Nicholas George

5f-1a:

5f-c:

**Scientific Progress**

1. A novel ICIS camera is described. This new camera is a completed new concept, unrelated to our recent highly successful EDOF work on the logarithmic asphere. The system works in the optical region where diffraction effects are important. The novel features of our camera include that it is a lensless system, and that it is capable of multi-wavelength imaging with only a monochromatic detector array. Additionally, this camera will operate at extremely low light levels. Moreover, since it is lensless, in principle it can operate over an extremely broad range of wavelength. This camera is just in the early stages of being reduced to practice. Wanli Chi will describe this camera at the annual meeting of the Optical Society of America in October. Recently a set of overheads describing this impressive new system was sent to Dr. Richard Hammond and we would respectfully advise that Wanli Chi is available to deliver a seminar on this material in a closed session at ARO at your convenience. We believe that this new system will have important impact on futuristic imaging systems. Finally, this capability of lensless infrared multi-spectral imaging promises a major advancement in remote sensing systems. Since the output of sophisticated, talented PhD scholars is a major factor in our research activities. Let me report on two doctoral scholars who were supported by funding from this ARO contract. The first is Dr. Wanli Chi who remains active in research at the University of Rochester under ARO sponsorship. He has been promoted to Assistant Professor of Optics (Research). We are working on a new project on coded aperture system. This new project involved testing a system consisting only a phase plate and detector array for imaging. An important feature of the new camera is its color imaging capability with mono-chrome detector array, and its potential in hyperspectral imaging. Secondly let me mention Dr. Kedar Khare who graduated in 2004 and then stayed as Research Scientist for 3 years. He made many important research contributions that have been reported earlier. He is presently conducting basic research in how to make the best possible medical images using MRI and computer tomography. One specific new topic of his is how to reduce the X-ray exposure level by a factor of 10. He is extending his basic earlier work on smapling that was described in his thesis. The PI and Optics faculty have nominated Dr Kedar Khare for the Lomb medal for an outstanding contribution to Optics before the age of 35.

2. In 2006 under ARO sponsorship, we published a polarization coding method for obtaining extended depth of field. This is separate and distinct from the logarithmic asphere work. Recently, we recognized that a lens system in which one creates an unbalanced optical path difference will also provide extended depth of field. This system is capable of providing EDOF in an extremely simple manner. A few annular rings of 10 micron thickness can be attached on to any existing lens. We are going to describe this technique at the annual meeting of the Optical Society of America in Rochester 2008 as itemized elsewhere in this report. Also, we are submitting a publication as soon as possible. Besides its simplicity, one advantage of this method is that it can provide a large increase in depth of field comparable to the log asphere.

3. A dominate interest in our Emerging Electronic Imaging Systems Laboratory (EEISL) is imaging through a turbulent medium as well as imaging through a fog like turbid medium. During the past year our research on speckle through thick diffuser has led us to the development of a novel thick diffuser consisting of tiny polystyrene particles immersed in gelatin. This diffuser is ideal in that it closely mimics a black body or an integrating sphere. While opal milk glass has been a standard thick diffuser in optics for many years, it is generally too diffuse. Actual imaging experiments are not really practical using opal milk glass. Our studies of this new type of thick diffuser have demonstrated that one can fabricate dilute thick diffusers. It is expected that this dilute thick diffuser will be very useful to the research community as they study imaging through a turbid medium. Practical examples are fog as well as tissue.

4. Research has continued on the infrared hologram at 10.6 microns. We have developed an excellent setup for recording high quality holograms in the infrared. Our present studies are directed to establishing the precision in depth resolution along the optical axis. For an object we are using gold wires sandwiched between 3 inch disks silicon. This simulates defect inspection method that might be applied to an ingot of silicon.

In summary of our research achievements for this contract, we briefly summarize as follows:

In the field of extended depth of field systems, we have been extremely successful in inventing and reducing to practice and technology transfer. During this contract period, new adaptation of the basic variable focal length system has been reported in first class peer review journals. It is now possible to make small  $f/\#$  systems that will stay in focus from 4 inches (10cm) to infinity. Many important improvements to telescope are likely to emerge in the next few years. Our basic research in this area has been completed. The new phase coded aperture system is still in the research stage, although its important practicality has also been demonstrated. This research is still ongoing. In imaging through a turbid medium like fog, we are just starting on a research project of great practical importance. Based on early research by Emmett Leith and Alfano, we feel that our novel thinking will lead to important research results that have great practical importance. Our research in this field is based on speckle concepts, careful new theoretical work and our novel space invariant 4F optical system for speckle metrology. We believe that a new optical modality for imaging is going to emerge from this research.

### **Technology Transfer**

